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The results of a two-year project to explore new methods for deposition of III-V semiconducting film on silicon substrates are summarized. Gas-source molecular beam epitaxy was used for the first time to achieve heteroepitaxy of InP on Si. The InP films contain low concentrations of impurities (< 400 ppb), luminescence under optical excitation, and exhibit high structural quality. Laser-assisted epitaxy was used for selective area growth of GaP and InP on Si using a new phosphorous precursor, and in situ removal of oxide on Si was achieved photochemically. Plasma-assisted chemical vapor deposition of AlN films has been carried out at low substrate temperatures using an electron beam to excite a remote plasma.

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Final Technical Report

for

AFOSR Contract #F49620-86-K-0021
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entitled

"Beam Assisted Fabrication of III-V/Si Monolithic Devices"

at

Colorado State University
Fort Collins, CO 80523

PI: Gary Y. Robinson
Co-PIs: George J. Collins
Raj Solanki (Oregon Graduate Center)

ABSTRACT

The results of a two-year project to explore new methods for deposition of III-V semiconducting film on silicon substrates are summarized. Gas-source molecular beam epitaxy was used for the first time to achieve heteroepitaxy of InP on Si. The InP films contain low concentrations of impurities (< 400 ppb), luminescence under optical excitation, and exhibit high structural quality. Laser-assisted epitaxy was used for selective area growth of GaP and InP on Si using a new phosphorous precursor, and in situ removal of oxide on Si was achieved photochemically. Plasma-assisted chemical vapor deposition of AlN films has been carried out at low substrate temperatures using an electron beam to excite a remote plasma.

Final Annual Report

"Beam Assisted Fabrication of III-V/Si Monolithic Devices"

The objective of this research project is to explore two new methods for deposition of III-V semiconducting films on Si substrates. Using gas-source molecular beam epitaxy (MBE) and photon-beam and electron-beam assisted metal-organic chemical vapor deposition (MOCVD), GaAs and other III-V films with abrupt heterojunctions are being formed epitaxially on Si, and by means of optical and electrical characterization the suitability of the resulting III-V/Si structures are being examined for use in monolithic devices.

<u>Gas-Source MBE</u> (Gary Y. Robinson, Colorado State University)

Gas-source MBE combines thermal cracking of the gaseous hydrides AsH_3 and PH_3 to produce molecular beams of As_2 and P_2, respectively, with conventional MBE technology for Group-III molecular beam production from effusion cells. The availability of both As_2 and P_2 beams allows incorporation of buffer layers of wide composition range and lattice parameters and for exploration of III-V materials grown by MBE on Si other than GaAs.

The major accomplishments of this program are summarized as follows:

- Established the first operational gas source MBE system at a U.S. University. The system consists of a commercial MBE system with custom designed gas cracker, gas flow control and delivery system, and UHV pumping for safe removal of hydrogen and the toxic hydrides.

- Achieved the first successful heteroepitaxy of InP on Si by MBE. Using three-inch wafers, optimum growth conditions have been determined and initial characterization indicates a dislocation density of 7×10^7 cm^{-2}, double crystal x-ray diffraction curves with FWHM of 435 arc sec, low temperature photoluminescence line widths of 6 meV, residual impurity concentrations of 2×10^{16} cm^{-3}, and specular morphology. Four strained-layer superlattices of InGaP/InP were used to buffer the 8% lattice mismatch between the InP active layer and the Si substrate.

Students Supported: Todd Crumbaker, Ph.D. candidate.

Richard Stave, MS, May 1989.

Publications and Conference Presentations:

1. T. E. Crumbaker, H. Y. Lee, M. J. Hafich, and G. Y. Robinson, "Growth of InP on Si Substrates by Molecular Beam Epitaxy," Appl. Phys. Letts. 54(2), 140 (Jan. 9, 1989).

2. G. Y. Robinson, "Gas-Source MBE Technology," (invited paper), First International Workshop on CBE/MOMBE/GSMBE, Sapporo, Japan, September 1988.

3. T. E. Crumbaker, M. J. Hafich, H. Y. Lee, and G. Y. Robinson, "Growth of InP on Si by Gas-Source MBE," Ninth Workshop on MBE, Purdue University, September 1988.

4. H. Y. Lee, T. E. Crumbaker, M. J. Hafich, G. Y. Robinson, M. M. Al-jassin, and K. M. Jones, "Characterization of InP on Si Grown by MBE," International Conference on Indium Phosphide and Related Materials, Norman, OK, March 1989.

Electron-Beam Assisted Deposition (George Collins)

The AFOSR/DARPA funding has been used to further develop e-beam assisted deposition of III-V semiconductors. The e-beam configuration used was a disc shaped ring that allowed for the generation of a circular plasma sheet. This was used to create a plasma remote from the introduction of the organometallic precursors such that the feedstock gases are not exposed to

the high energy region of the plasma. The remote plasma then decomposes the precursors via excited radical collisions, VUV photons, and for the case of remote hydrogen plasmas, reaction with atomic hydrogen. The deposition done by this technique are at low temperature and not dependent on substrate temperature to thermally drive the deposition.

Specifically the remote plasma has been used to deposit AℓN films at low temperature on thermally mismatched substrates. Comparisons to excimer laser deposited films were done displaying a higher achievable quality. (See T. Sheng, Appl. Phys. Lett., **52**, 576 (1988)).

The use of the remote plasma has been explored in the decomposition of Trimethylgallium (TMGa) via ex-situ Mass Spectrometer (T. Sheng, et al., in preparation). After demonstrating the technique for the deposition of ZnSe (MRS Fall 1988 Meeting, K. Tokuda, et al.) with organometallic precursors, the byproducts of the remote plasma decomposition were studied to understand the conversion to stable organics. TMGa with the hydrogen plasma mostly yielded methane similar to the thermal decomposition. TMGa exposed to remote helium plasmas yielded mostly ethene, due to the lack of available hydrogen. This research activity is ongoing.

Students Supported: Ten-yu Sheng, M.S., August 1989.
Bert Pihlstrom, Ph.D. Candidate.

Publications:

1. "Disk Plasma Assisted Chemical Vapor Deposition of Aluminum Nitride," T. Sheng, Z. Yu and G. J. Collins, Appl. Phys. Letts. **52**, 576 (1988).

2. "Mass Spectroscopic Studies of the Decomposition of Trimethylgallium with Remote Hydrogen and Helium Plasma," T. Sheng, B. Pihlstrom, Z. Yu and G. J. Collins, to be submitted to Appl. Phys. Letts.

<u>Laser-Assisted Epitaxy of III-V Compounds</u> (Raj Solanki, Oregon Graduate Center)

One of the objectives of the proposed investigation was to explore use of lasers for achieving epitaxial growth of III-V compounds on silicon. This approach was proposed to demonstrate two unique features: (a) spatially selective deposition that can be achieved without the use of lithographic masks and (b) low temperature epitaxy. Both these objectives were achieved utilizing an Argon ion laser and an excimer laser. For safety reasons our investigation was concentrated on growth of GaP and InP using a new phosphorus precursor of significantly lower toxicity than PH_3 or AsH_3. Our major accomplishments are listed below.

1. Homoepitaxial growth of microscopic lines and pads of GaP and InP using a focused laser beam and a new phosphorus precursor.
2. In-situ oxide removal of Si using a low temperature photochemical process.
3. Selective heteroepitaxy of GaP on silicon.
4. Excimer laser assisted epitaxy of GaP and InP microstructures using projection lithography (i.e., mask outside the reactor).
5. Laser-assisted growth of doped epilayers. Characterization of diodes fabricated show them to be comparable to those grown by conventional means but at much higher temperatures (~300°C higher).
6. Optical absorption and mass spectroscopy of the laser dissociation of the metallorganic precursors investigated. Modeling is progressing well.

Students Supported: U. Sudarsan, Ph.D. candidate.

Publications and Conference Presentations:

1. "Laser Induced Homoepitaxy of GaP," Appl. Phys. Lett. <u>52</u>, 919 (1988).

2. "Selective Heteroepitaxy of GaP on Silicon," J. Crystal Growth 94, 978 (1989).

3. "Observation of Five-Fold Symmetry in GaP," Materials Letters, to be published.

4. "Excimer Laser Assisted Epitaxy of III-V Compounds," submitted for publication to Applied Physics A.

5. "UV Photon Assisted Epitaxy of Compound Semiconductors," Oregon Materials Symposium, April 1989.

6. "Argon Ion and Excimer Laser Induced Epitaxy of GaP," Materials Research Conference, Dec. 1988.

7. "Photon Induced Heteroepitaxy of III-V Compounds," Gordon Conference, March 1988.

8. "Photon-Assisted Processing of Electronic Materials," Atomic and Molecular Processing of Electronic and Ceramic Materials Symposium, Aug. 1987.

Several manuscripts based to this investigation, e.g., spectroscopy, modeling, and InP epitaxy will be submitted for publication this summer.